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FIRE-INDUCED RE-RADIATION UNDERNEATH PHOTOVOLTAIC ARRAYS ON FLAT ROOFS

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ABSTRACT

The impact of the reflection of fire-induced heat from a gas burner was studied experimentally to gain knowledge on the interaction between photovoltaic (PV) panels and a fire. The heat flux was measured in a total of eight points at the same level as the top of the gas burner. The gas burner was placed underneath the centre of a PV panel and the eight points were measured in symmetrical pairs of two at four different distances from the burner. The heat release rate from the gas burner was increased stepwise every four minutes. The measurements were made underneath a PV panel installed in a geometry similar to a commercial East-West orientated mounting system and was compared to a baseline test without the re-reflection from the PV panel. A significant increase of the received heat flux was noticed and the trend indicated an ascending percentage-wise difference as a function of an increased heat release rate.
Contrary to the basic view factor theory, the received heat flux was higher underneath the most elevated part of the PV panel, and this occurred due to two important flame related reasons: 1) the deflection of the flame towards the most elevated part of the panel, resulting in an increased amount of radiation from the flame towards the surface; 2) A non-homogeneous distribution of the temperature on the PV panel surface, due to the deflected flame, and thereby a non-homogeneous emission from the heated PV panel.
Finally, it was seen that two similar tests conducted with respectively a brand new PV panel and a PV panel tested for the fourth time, showed very comparable results, except during the period when the thin combustible film underneath the new PV panel was burning. This resulted in a higher heat flux during that period and implies that the results presented herein are conservative in that they are lower than what can be expected in case of a real fire hazard, where the PV panel is by definition involved in the fire for the first time. It can be concluded that PV panels can have a significant contribution in roof fires, as they stimulate fire spread over the roof on which they have been mounted. These findings emphasise that the risk related to the installation of PV panels is not only associated with the increased fire load and possibility of ignition, but largely also with the changed fire dynamic surroundings of the roof construction.

INTRODUCTION

An increased focus on renewable energy, a desire to gain good publicity and especially the possibility of decreasing the energy cost, in a world where the demands of energy increase, are important reasons why photovoltaic (PV) panels become more and more popular. For companies with large flat roof constructions on buildings it can even be cost-beneficial, because it allows for utilization of the unused space on the top of their properties. An initiative along these lines is the recent suggestion to replace all Dutch asbestos roofs with PV panels [1].

However, the installation of PV arrays introduces new and not yet well-studied fire related risks to the roof construction, which is of great interest for all parties involved in PV related power, from the manufacturer of the panels to the owner of the facilities and their insurance companies. A risk assessment related to the

Italian national fire services guidelines by Cancelliere [2] divides current studies into three main domains: (1) ignition, (2) propagation of the fire and (3) the safety of personnel, including fire fighters.

The installation of large PV arrays and thereby large power generating DC systems introduces a risk of electronic malfunctions and thereby a possibility of ignition and fire. Wohlgemuth and Kurtz [3] divided the causes of fire hazards into three categories: (1) hot spots, (2) high series resistance and (3) arching. Pandian et al. [4] studied the consequence of shading faults on PV panels and concluded that the temperature of the PV panel is a potential hazard, especially in the hydrocarbon industry. Solar America Board for Codes and Standards (Solar ABCs) and UL studied the Bakersfield fire [5] and suggested that a current of 1000 ampere in a small, unprotected 10 AWG wire was the source of ignition. In general, it seems to be accepted to assume an electric malfunction to be the main cause of PV related fires, which is why there exists extensive studies in the electronics industry (e.g., Zhao et al. [6], who made a fault analysis of PV arrays to avoid safety hazards).

Each element added to a roof construction can be seen as an addition to the fire load. A PV panel's reaction to flames is tested in the European standard IEC 61730-2:2016 [7] and the American equivalent UL 1703 [8]. Despinasse and Krueger [9] found that the current tests are based on non-easily reproducible test methods and are in the development of a method where they test the PV panel's reaction to a propane flame. Despite the fact that parts of a PV panel are combustible, the current authors have earlier concluded that the PV panel, as a fuel load, does not represent a large fire hazard for a roof construction, because combustible materials represent a minor amount of the panel's total mass [10].

The safety for fire fighters has been addressed by SFPE [11], UL [12] and The Fire Protection Research Foundation [13]. The risk of being electrocuted during fire extinguishment actions has furthermore been studied by Tommasini et al.[14], where they concluded that panels with a voltage up to 1000 V DC could be extinguished safely, by respecting safety distances. Lastly, the Solar ABCs have concluded that the installation of PV panels on sloped roof constructions reduced the fire related properties of the subjacent material [15].

Based on the approach that the PV panels do not contribute with a significant fire load to the roof construction, it is of interest to study why large fires involving PV installations are occurring on regular basis. This increase in PV-related fires, which can, for example, be seen from data based on incident reports from the Italian National Fire Corporation [16], indicates that the installation of PV arrays changes the boundary conditions of the fire by reflecting a significant fraction of the heat back towards the surface of the roof construction instead of into open air. The matter of a possible propagation of fire, without regard to the actual source of the fire, strongly depends on how the surrounding environment responds to the ignition, which once again depends on the critical heat flux for ignition of the adjacent materials. The reflected heat would be added to the heat flux from the fire, resulting in a increased total heat flux towards the top of the roof construction, and when or if the total heat flux exceeds the critical heat flux for the subjacent material, it will ignite. Thus, the propagation of a fire beyond the point of ignition, say from a faulty wire, basically depends on the ratio between the critical heat flux of the unignited material versus the heat flux received from the surroundings. The hypothesis herein is therefore that a propagation of a fire can only occur in a (fire proofed) roofing membrane if the membrane's critical heat flux is exceeded by the sum of the heat from the ignition source or burning roofing membrane and the heat reflected by the PV panels.

The main aim of the experiments presented herein is therefore to examine how the installation of a PV panel influences the energy release from a realistic flaming fire source, which was represented by a gas burner. The gas burner made it possible to define different steady state heat release rates (HRR), and these well-controlled HRRs enabled the possibility of a comparison between the heat flux received at the same spot, with and without the reflection from the PV panel.

THEORY

A fire on a roof construction would influence the surroundings with the three types of heat transfer: conduction, convection and radiation. Without external impacts, such as wind, it is expected that only the conduction and a fraction of radiation will affect the nearby roofing materials, whereas the convection and most of the radiation will be transferred into the open air. By adding a PV installation above the fire on the roof construction, large parts of the radiation will either be absorbed by the panel or reflected back towards the surface of the roof construction that is located underneath the panel. The absorbed heat, together with the heat received from convection, will increase the temperature of the panel resulting in an enhanced amount of emission according to the Stefan-Boltzmann law.

Based on the view factor theory and an assumption of a homogenously distributed temperature over the entire PV panel surface, it is possible to calculate the radiative heat transfer between the solid surface *AC* and the point *D* in Fig. 1. The view factor in point *D*, as a function of the distance between *B* and *D* can be seen in Fig. 2 and Fig. 3 for respectively different angles, θ, and elevations, h_E, of the solid. The graphs indicate that the received heat flux by radiation emission from the heated panel decreases as a function of an increased elevation or a decreased angle. It is furthermore noticed that the view factor is largest underneath the least elevated part of an inclined panel, as expected.

In case of an East-West orientated PV installation, a convectional contribution of heat from the flow of hot air underneath the installation is expected, possibly combined with radiation from the smoke. Herein, the different heat sources are treated separately, because it is the combined additional heat that represents increased hazard to the subjacent surface, and the main objective is to examine whether or not the additional contribution of heat is significant for the propagation of a possible fire.

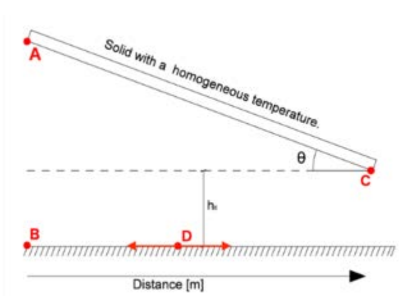

Figure 1 - Simplified set-up of a solid with the angle θ and the elevation h_E above a surface.

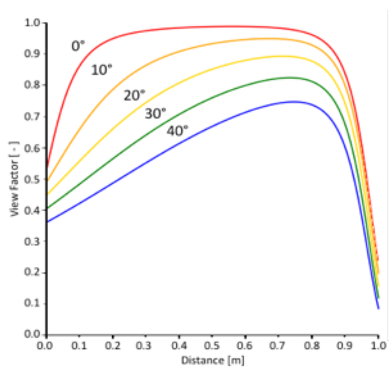

Figure 2 – Theoretical view factor as a function of the distance between point B and D, the angle θ and a fixed elevation of h_E = 0.1m in Fig. 1.

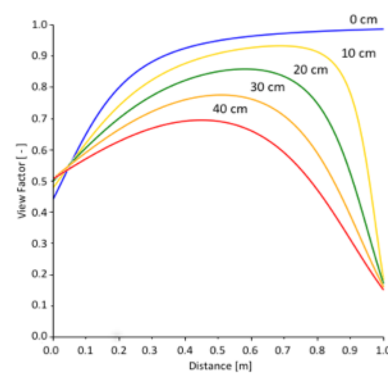

Figure 3 – Theoretical view factor as a function of the distance between point B and D, the elevation h_E and a fixed angle of $\theta = 10°$ in Fig. 1.

EXPERIMENTAL SETUP AND APPROACH

The setup seen in Fig. 4 consist of a Bosch Rexroth modular system, which made it possible to change the elevation and angle of the PV panels by adjusting h_L and h_R. Two PV panels with dimensions of $1.0\ m \times 1.7\ m$ were tested. The panels were poly-crystalline panels designed with a front layer of glass and polymer backsheet encasing the PV cells. The main panel was stabilized by a 40 mm aluminum frame and the panel could be connected to a PV system via two connection cables. Because the objective was to test the PV panel's influence on the heat flux received at the subjacent surface it was decided to cut both connection cables and the thereby avoid an additional, but non-reproducible, fire load from the panels.

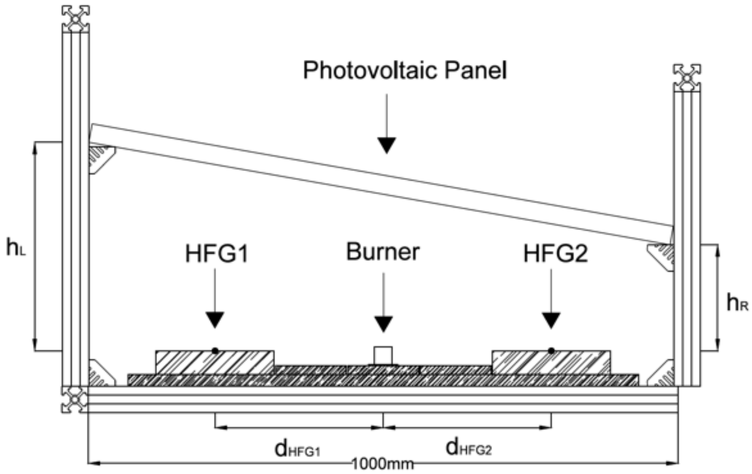

Figure 4 - Schematic of the setup used to study the reflection. The hatched areas underneath the Burner and the Heat Flux Gauges (HFG) are made up of non-combustible insulation.

A scaled sandbox gas burner was placed in the center of the setup, using LPG with minimum 90% propane and maximum 10% butane as fuel. Due to uncertainty with respect to the exact composition of LPG, the HRR has been calculated using the heat of combustion (ΔH_C) for propane. It is noted that the error is small, given the very similar ΔH_C values for propane and butane (respectively $46.3\ MJ\ kg^{-1}$ [17] and $45.7\ MJ\ kg^{-1}$ [17]). The gas flow was controlled by a Bronkhorst flow meter with a maximum flow rate of $10\ l/s$ and thereby thus a maximum HRR of $14\ kW$ from the burner. Due to the sensitivity of the used Heat Flux Gauges (HFGs), the maximum HRRs were not used.

The HFGs were water cooled Hukseflux SBG01 thermal sensors with a working range around $5\ kW/m^2$. As seen from Fig. 4, the HFGs were installed in a $40\ mm$ thick board of non-combustible insulation to avoid unintended heating from the sides. The insulation boards with the HFGs could be moved horizontally on top of the subjacent second layer of non-combustible insulation – making it possible to measure the heat flux in different positions for each test. The sensitive part of the HFGs were furthermore elevated to the same height as the top of the burner to avoid shadowing effects. Both the water supply to the HFGs and the gas supply to the burner were placed underneath the insulation to prevent influence from the heat.

Test matrix

An overview of the conducted tests is shown in Tab. 1, where the 17 tests have been divided into five subgroups. The difference between the results in tests series A and B was used to examine the difference between the heat flux received at the same distances from the gas burner, with and without the influence of the PV panel. In test series B the panel was placed in a geometry similar to the mounting system used for an East-West orientated array and the elevation and angle of the panel were changed in respectively test series D and E.

Table 1 – Schematic overview of the experiments conducted. All dimensions are in cm.

A: Baseline Test – No PV

Test #	h_L	h_R	d_{HFG1}	d_{HFG2}
1.1	-	-	-28.5	28.5
1.2	-	-	-22	22
1.3	-	-	-16	16
1.4	-	-	-11	11

B: Standard Mounting System

Test #	h_L	h_R	d_{HFG1}	d_{HFG2}
2.1	32	9	-28.5	28.5
2.2	32	9	-22	22
2.3	32	9	-16	16
2.4	32	9	-11	11

C: Similar to test 2.4 – with new PV

Test #	h_L	h_R	d_{HFG1}	d_{HFG2}
3.1	32	9	-11	11

D: Changed height

Test #	h_L	h_R	d_{HFG1}	d_{HFG2}
3.2	27	4	-11	11
3.3	27	4	-28.5	28.5
3.4	37	14	-11	11
3.5	37	14	-28.5	28.5

E: Changed height

Test #	h_L	h_R	d_{HFG1}	d_{HFG2}
4.1	27	9	-28.5	28.5
4.2	27	9	-22	22
4.3	37	9	-16	16
4.4	37	9	-11	11

Approach

Each test was made with an increase of the HHR by 1 kW for approximately 4 minutes each – a slight difference of the time intervals occurred because it was a manual process. All of the tests were running with 0 kW for an initial start-up period to ensure the heat flux received from the surroundings was constant. The PV panels were kept at room temperature for at least 40 minutes between each test to avoid the heat from a previous test to influence the following test. Because of the sensitivity of the used HFGs and because only two new PV panels were available for the tests, it was decided to stop the tests if the received heat flux underneath the PV panels exceeded 7.5 kW for a continuous period. The decision was primarily decided to protect the HFGs but also to avoid structural damage of the panels, including broken glass, which could influence the results. The tests in series B were carried out with the same PV panel whereas the tests in series D and E were conducted with two different panels.

RESULTS AND DISCUSSION

Influence of the PV panel

The actual experimental setup can be seen in Fig. 5. It is important to notice the deflection of the flame towards the most elevated part of the PV panel. The consequence of the deflected flame can be seen in Fig. 6 where the received heat flux is plotted as a function of time, and therefore on the HRR from the gas burner.

In Fig. 6, it is seen that the highest heat flux is measured by HFG1, positioned underneath the most elevated part of the panel (see Fig. 5), which means that the view factor theory alone (Fig. 2 and Fig. 3) cannot explain the results. Furthermore, Figure 6 shows that the increase in HRR from the gas burner results in an

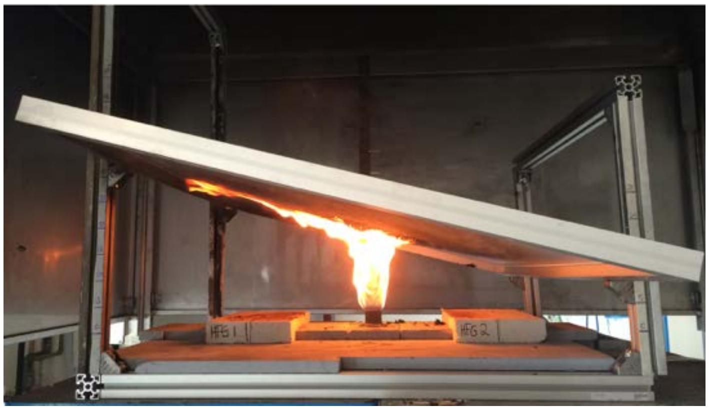

Figure 5 - Photo of the setup. Notice how the flame is deflected upwards underneath the PV panel.

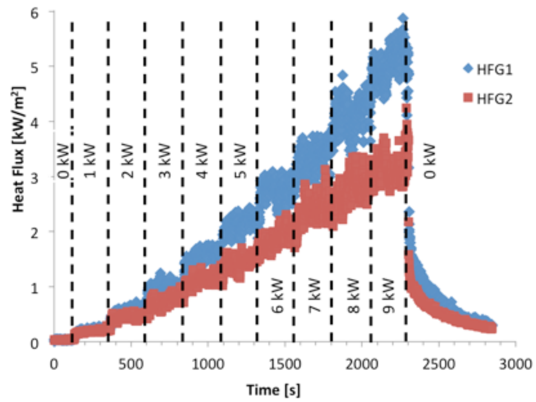

Figure 6 - Raw data from test 2.2: the received heat flux [kW/m^2] is plotted as a function of time [s]. The vertical black dotted lines indicate the changes of the HRR over time.

increase of the received heat flux on the subjacent surface. In addition, the fluctuations increase for increased HRR, and these fluctuations in the measured heat fluxes probably relate to fluctuations of the flame length from the gas burner. From the last period in the measurements (Fig. 6) it is seen that the emission from the PV panel, due to its increased temperature, is limited to approximately *2 kW/m^2* immediately after interruption of the gas flow (and thereby the almost immediate disappearing of the flame). As the panel cooled down, the measured radiation emission descends towards it original state of approximately *0 kW/m^2*.

In order to study the distribution of the heat flux measurements as a function of the location, the measurements were averaged. To that purpose, the averaging was performed over 2 minutes per imposed HRR, once a new steady state had been obtained after increasing the HRR. These averaged values are then assumed to be constant, representative for that imposed HRR. If this heat flux exceeds the critical heat flux for the subjacent material, it is assumed to result in ignition and thereby a propagation of the fire.

The average received heat flux was calculated for all HRRs and all positions of the HFGs, making it possible to plot the measured heat flux as a function of the distance to the gas burner for test series A and B, as seen from Fig. 7. From subfigure A, which is the baseline test without the PV panel, it can be noticed that the measured heat flux is almost symmetrically distributed around the centre of the gas burner which is placed at a distance of 0 cm. The measurements at the left side of the gas burner are slightly higher than the right side of the burner, though. This is probably due to a limited occasional draught towards the left side of the setup in the laboratory. The difference is small, but will be kept in mind for the conclusion. The measurements from test series B, with a PV panel installed in a geometry similar to commercial available mounting system, are shown in subfigure B. A significant increase of the heat flux is observed at all locations, when compared to the measurements without PV panel. As mentioned above, all the measurements underneath the most elevated part of the panel are higher than the measurements at the same distance from the burner underneath the least elevated part of the panel. This indicates the importance of the heat transfer by the flame, as mentioned above. This observation, along with the very fast decrease of the measured heat flux when switching off the burner (Fig. 6, final period in the experiments) emphasises that the emission from the panel, compared to the heat transfer from the flame, is only a limited contributor to the total heat flux towards the subjacent surface.

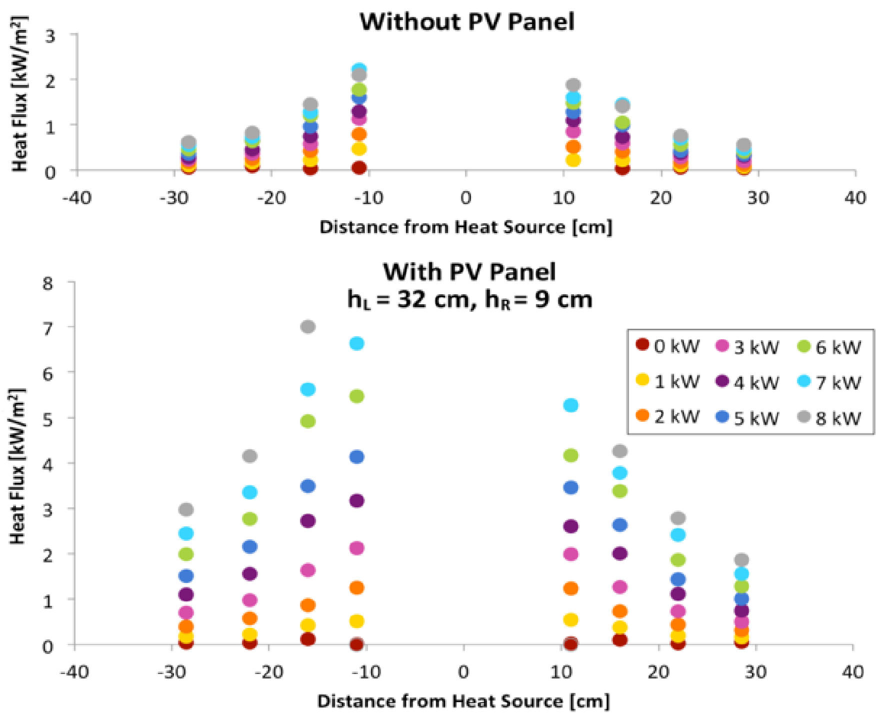

Figure 7 – Averaged measured heat fluxes for test series A (top) and B (bottom). The Heat Flux received as a function of distance to, and HRR from, the heat source. Each colored dot defines a HRR and the gas burner is placed at the distance of 0 cm from the heat source.

With the assumption that the amount of convective heat is limited due to the distance of the panel from the roof surface (Fig. 5) and the fact that there is no accumulation of hot smoke, the differences between the measured heat fluxes at both sides of the gas burner are related to the radiation from the deflected flame from the gas burner. The influence of the flame can also be seen in Fig. 8, where the percentage-wise increase of the received heat flux is plotted as a function of the HRR and the distance from the gas burner, as seen from equation 1.

$$I(D,\dot{Q}) = \frac{\dot{q}''_{PV}(D,\dot{Q}) - \dot{q}''_{Base}(D,\dot{Q})}{\dot{q}''_{Base}(D,\dot{Q})} \times 100\% \qquad (1)$$

Where:

$I(D,\dot{Q})$: is the percentage-wise increase of the heat flux *[%]*

D: is the distance from the gas burner *[cm]*

$\dot{Q}$: is the HRR from the gas burner *[kW/m^2]*

$\dot{q}''_{PV}(D,\dot{Q})$: Is the heat flux received for a given distance and HRR in test series B *[kW/m^2]*

$\dot{q}''_{Base}(D,\dot{Q})$: Is the heat flux received for a given distance and HRR in test series A *[kW/m^2]*

A consistent observation for the plot is that the percentage-wise increase of the heat flux continues to grow for the three most distant positioned HFGs at the left side of the gas burner (i.e., underneath the most elevated part of the PV panel at distances of -28.8 cm, -22 cm and -16 cm), whereas the increase stabilises for the other positions (at values between 180% to 250% of the heat flux that would have been received without the panel). The continued growth, as a function of HRR, for the HFG positioned at the distances of

-16.0 cm, -22.0 cm and -28.5 cm probably occurs due to a HRR-related increase of the deflected flame length. The view factor for radiation from the flame increases significantly as the flame becomes longer, in particular when it reaches a position such that the heat flux meters were directly underneath the flame. Once this took place, the received heat flux hardly increased with further increase of the HRR from the burner, again confirming that the flame radiation was the dominant factor. This also explains why the heat fluxes at the right hand side stabilised quickly and did not change significantly: the view factor from the flame hardly changed with an increased HRR from the burner. Only the emission from the panel increased, due to higher temperatures of the PV panel, caused by the higher HRR from the burner. Visual observations from the experiments supports this.

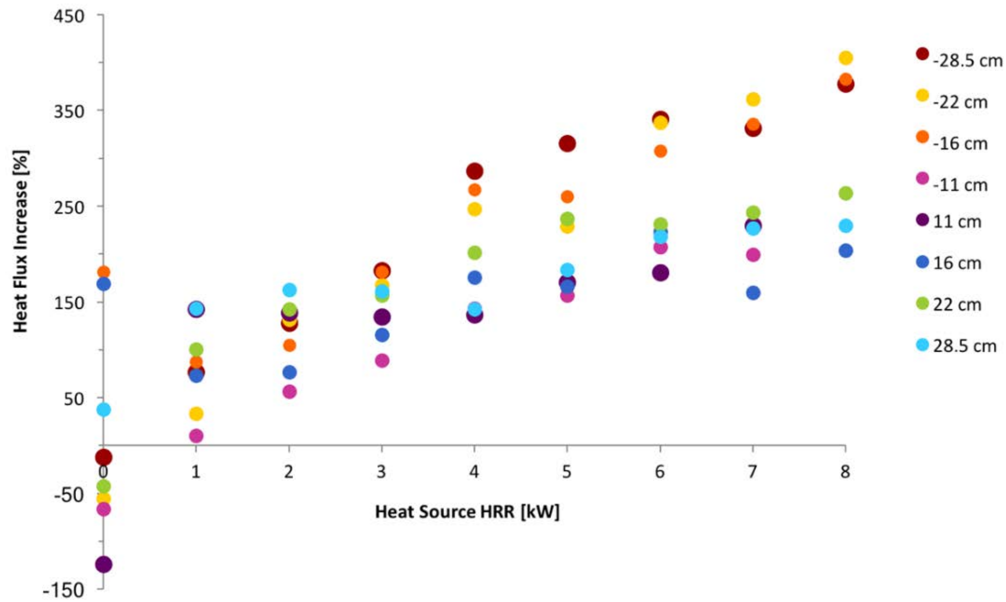

Figure 8 – Overview of the percentage-wise increase of heat flux, as a function of the HRR from the gas burner, measured in respectively the baseline test (test series A in Tab. 1) and underneath the PV panel placed in a standard mounting system (test series B in Tab. 1).

Reproducibility of tests

The performance of the similar tests 2.4, with a reused panel, and 3.1, with a brand new panel (Tab. 1), made it possible to assess the effect of reusing panels in the experiments. Based on the raw data measurements it was not possible to verify the similarity using a 2-sample z-test with a 10 % level of significance. Figure 9 therefore plots a 2-dimensional scatter diagram of paired data sets for the heat flux as received by the two heat flux gauges.

The diagram illustrates a good linear relation between the two tests, with two clearly deviating points, encircled by green circles, for the HRR of 4 kW. This corresponds to a period where the PV panels backing material burns, so there is an additional HRR. Ignoring these 2 points, the slope of the two trend lines indicate almost no difference between the heat flux underneath the new PV panel, compared to the panel tested for the fourth time. This confirms once again that the heat transfer from the flame is dominant.

However, during the burning period, the average heat fluxes measured underneath the brand-new PV panel was around 35 % higher. Based on these observations, it can be concluded that the current measurements are representative for periods while the PV panels are not burning, and therefore are on the lower side of what can be expected during an actual fire (where the PV panels are by definition brand new with respect to fire). The increase occurred due to the combustion of the thin film on the backside of the PV panel resulting in a short term growth of the heat flux.

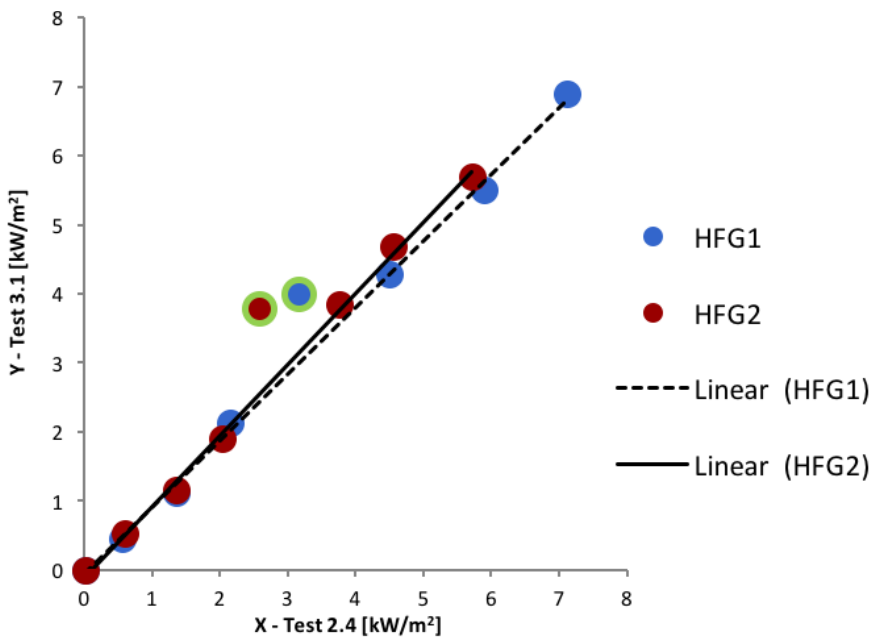

Figure 9 - Two-dimensional scatter diagram of the paired data set from test 2.4 and 3.1, with and without the paired data for a HRR of 4 kW. The two green lines encircle the two measurements made with a HRR of 4 kW and the two linear trend lines ignores these two measurements.

CONCLUSION

Based on experiments, where the received heat flux from a gas burner was measured at the nearby surface with and without the influence of a photovoltaic panel installed above the flame, it was seen that the installation of the PV array significantly increased the heat flux received on the subjacent surface. Contrary to the expected distribution of heat from view factor calculations, it was observed that the heat from, and the deflection of, the flame defined the area of the maximum heat flux. For a fire-induced heat source placed underneath an angled PV panel the maximum heat flux thereby occurred under the most elevated part of the panel, which is where the flame deflected.

PV panels can have a significant contribution in a fire hazard, as they stimulate fire spread over the roof on which they have been mounted. The current findings emphasise that the risk related to the installation of PV panels is not only associated with the increased fire load and possibility of ignition – but largely also with the changed fire dynamics on the roof construction.

Finally, the results could form the basis of a discussion regarding the level of fire related properties for roofing materials used underneath PV installations on flat roof constructions – as an improved reaction to fire performance of the roofing membranes could decrease the possibility of propagation underneath the arrays.

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